



# BR and direct CP asymmetries of charmless decay modes at the TeVatron

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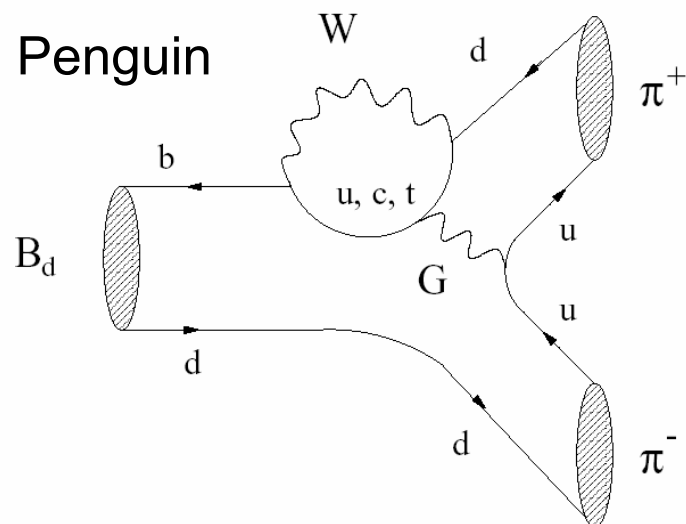
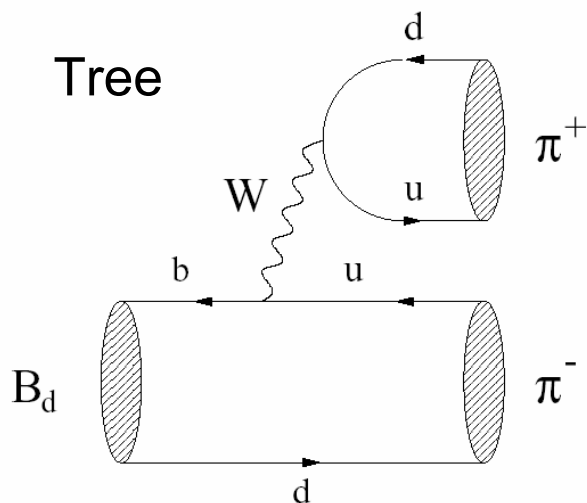
On behalf of the CDF collaboration



# Charmless

## $B^0/B^0_s \rightarrow PP$ ( $\pi\pi/K\pi/KK$ )

- Interpretation of B results often plagued by uncertainties from non-perturbative QCD uncertainties.
- Joint study of  $B^0$  and  $B^0_s$  decays into 2-body charm-less ( $\pi\pi/K\pi/KK$ ) plays a key role, related by subgroup of SU(3) symmetry.
- Until the beginning of the planned Y(5S) run at Belle only CDF has simultaneous access to  $B^0_s$  &  $B^0_d$  (and baryons too) decays thus exploiting an original physics program complementary to the B-factories





# Some specific motivations

- These modes include  $B^0 \rightarrow K^+ \pi^-$ , where the direct CP asymmetry was observed for the first time in B sector (B-Factories).
- Large ( $\sim 10\%$ ) effect established, but still many things to understand, i.e. asymmetry in  $B^0$  not compatible with  $B^+$  as expected. [Gronau and Rosner, Phys. Rev. D71:074019, 2005]
- Compare rates and asymmetries of  $B^0 \rightarrow K^+ \pi^-$  and  $B_s^0 \rightarrow K^- \pi^+$  unique to CDF – to probe NP with minimal assumptions, just SM. [Lipkin, Phys. Lett. B621:126, 2005]
- Rate of  $B_s^0 \rightarrow K^+ K^-$ , compared with  $B^0 \rightarrow K^+ \pi^-$  rate may shed light on the size of SU(3) symmetry breaking. [Matias, Virto, Descotes-Genon, PRL97, 061801, 2006], [Khodjamirian et al. PRD68:114007, 2003]
- Currently accessible BRs (i.e.  $B^0 \rightarrow \pi^+ \pi^-$  and  $B_s^0 \rightarrow K^+ K^-$ ) may provide useful information related to the angle  $\gamma$  through comparison between CDF measurements and the regions allowed by the theory. [Fleischer and Matias PRD66: 054009, 2002], [London and Matias PRD70:031502, 2004]



# CDF II at the TeVatron ( $@\sqrt{s} = 1.96$ TeV)

## TeVatron

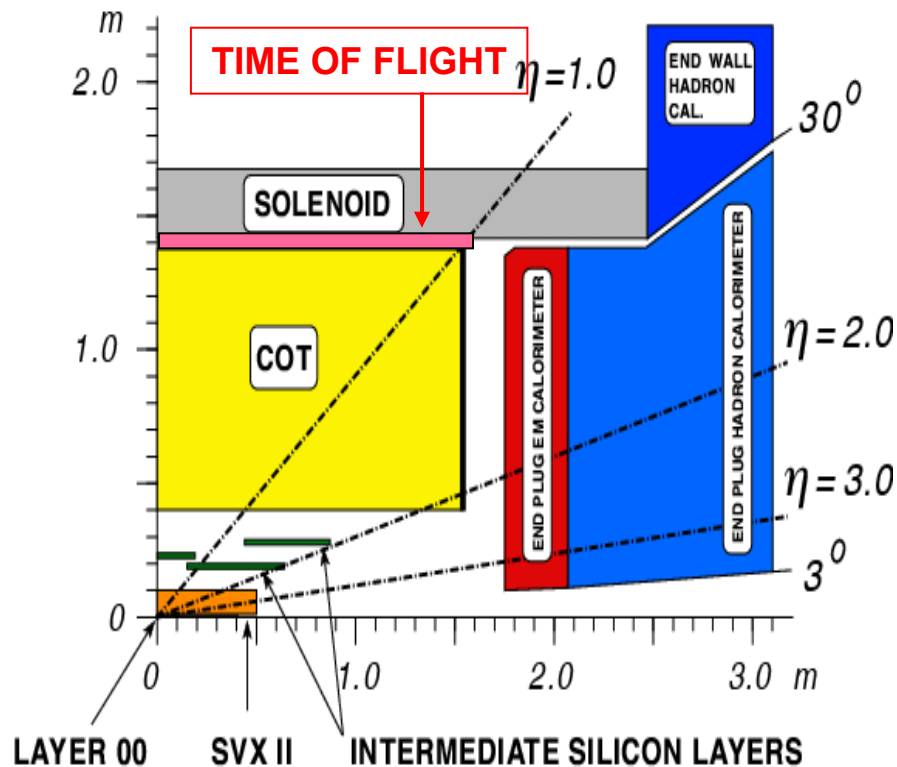
- p-pbar collisions
- record peak is  $L_{\text{inst}} = 2.37 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- $\sim 20 \text{ pb}^{-1} / \text{week}$  recorded on tape

## CDFII (Tracking):

- Central Drift chamber
  - $\sigma(p_T)/p_T^2 \sim 0.1\% \text{ GeV}^{-1}$
  - PID from  $dE/dx$
- Silicon Vertex detector
  - I.P. resolution  $35\mu\text{m}@2\text{GeV}$

## CDFII (Trigger):

- **Powerful triggers based on impact parameters and transverse B decay length (see A. Annovi's talk)**



Results here use  $\sim 1 \text{ fb}^{-1}$

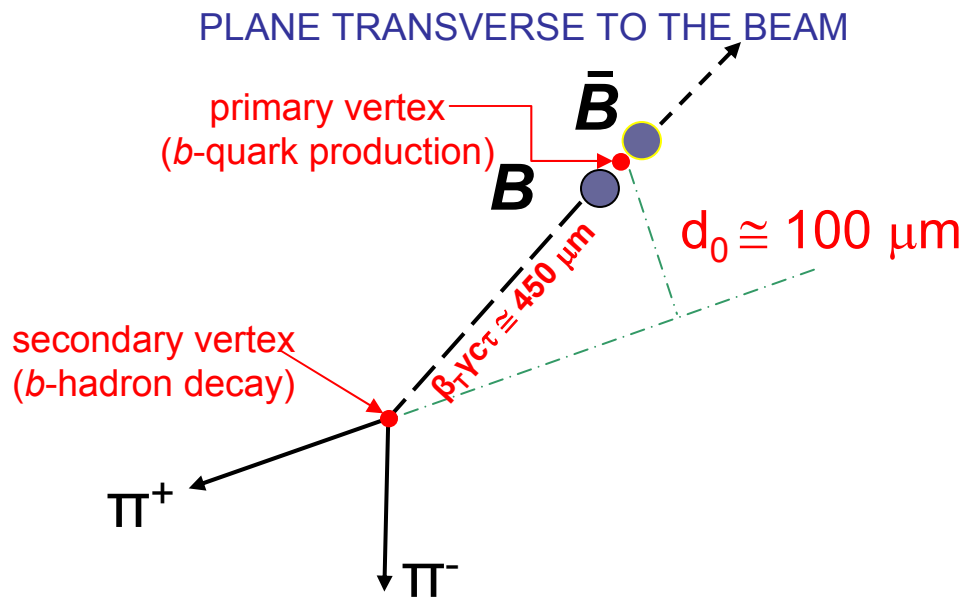


# B hadron signature

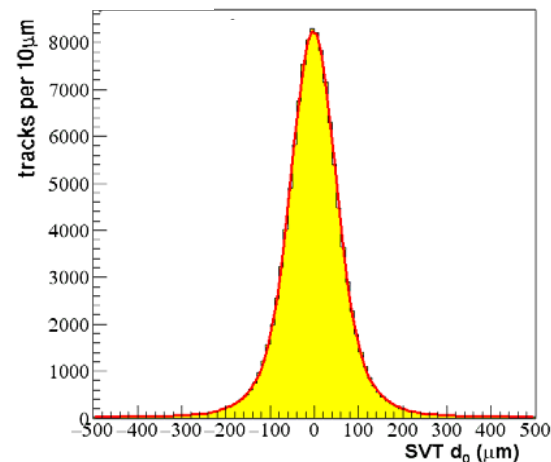
“Long” ( $\sim 1.5$  ps) lifetime of  $b$ -hadrons: a powerful signature against light-quark background.

For the first time, trigger HF without leptons: rare hadronic  $B$  decays. Cut online (L2 trigger) on impact parameter  $d_0$ (track).

Very high-purity samples of hadronic  $B$  (and  $D$ ) decays.



$$\sigma(d_0) = 48 \mu\text{m} = 35 \text{ [SVT]} \oplus 33 \text{ [beam-spot size]}$$



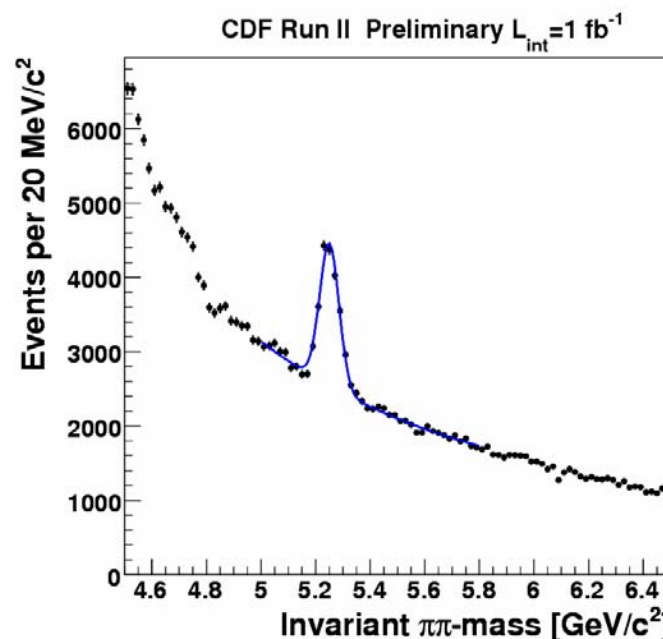


# Trigger confirmation

## TRIGGER REQUIREMENTS

- Two oppositely-charged tracks (i.e.  $B$  candidate) from a long-lived decay:
  - track's impact parameter  $> 100 \mu\text{m}$ ;
  - $B$  transverse decay length  $> 200 \mu\text{m}$ ;
- $B$  candidate pointing back to primary vertex:
  - impact parameter of the  $B < 140 \mu\text{m}$ ;
- Reject light-quark background from jets:
  - transverse opening angle  $[20^\circ, 135^\circ]$ ;
  - $p_{T1}$  and  $p_{T2} > 2 \text{ GeV}$ ;
  - $p_{T1} + p_{T2} > 5.5 \text{ GeV}$ .

Signal ( $\text{BR} \sim 10^{-5}$ ) visible with just offline trigger cuts confirmation:



a bump of  $\sim 8500$  events  
with  $S/B \approx 0.7$  (at peak)  
in  $\pi\pi\pi$ -invariant mass



# Cuts optimization

Optimize the cuts by minimizing the expected statistical uncertainty on what we are about to measure. Its expression  $\sigma(S,B)$  is determined from actual uncertainties observed in analysis of TOY-MC samples.

For any combination cuts, evaluate the above score function; optimal cuts are found when the functions reach the minimum. Signal yield  $S$  is derived from MC simulation while background  $B$  is estimated from mass sidebands on data.

Here 2 sets of cuts optimized to measure:

- (1) the direct  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$
- (2) to observe the  $B^0_s \rightarrow K^- \pi^+$  and measure the  $BR(B^0_s \rightarrow K^- \pi^+)$ .

gain in resolution with respect to the usual score function  $S/\sqrt{(S+B)}$  is  $\sim 10\%$  for  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$  and  $\sim 27\%$  for  $BR(B^0_s \rightarrow K^- \pi^+)$ .

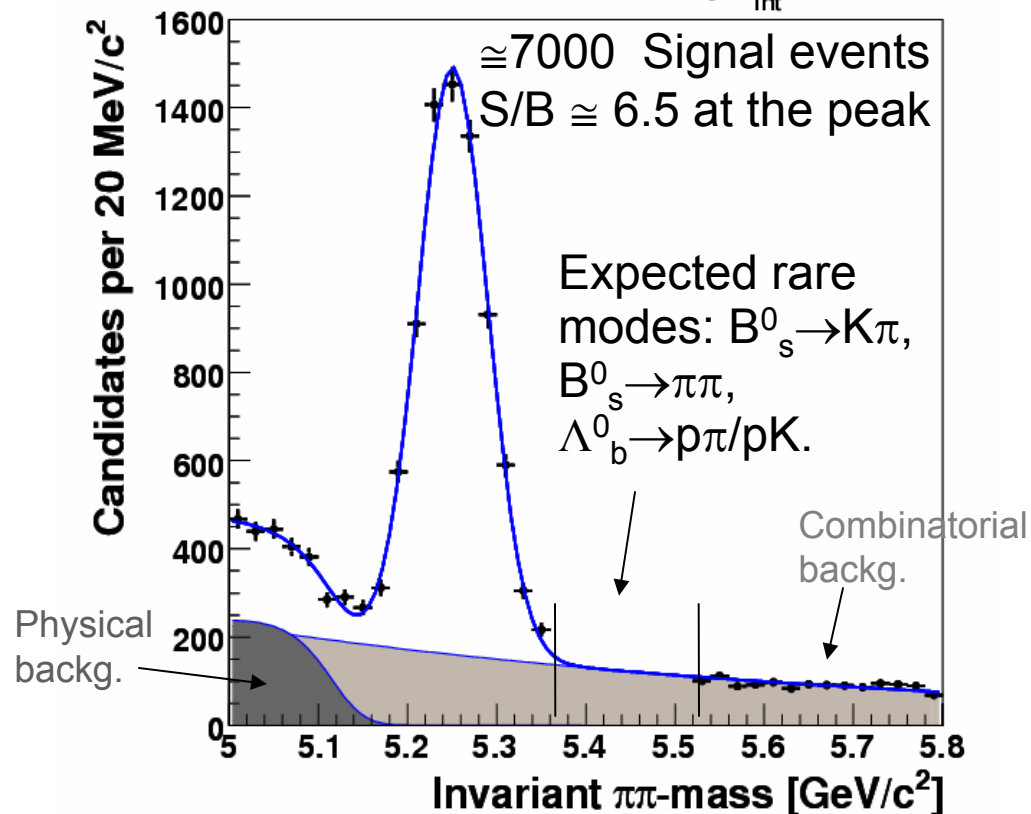


CP Asymmetry in  
 $B^0 \rightarrow K^+ \pi^-$  decays  
and  
 $BR(B^0 \rightarrow \pi^+ \pi^-)$  and  $BR(B_s^0 \rightarrow K^+ K^-)$



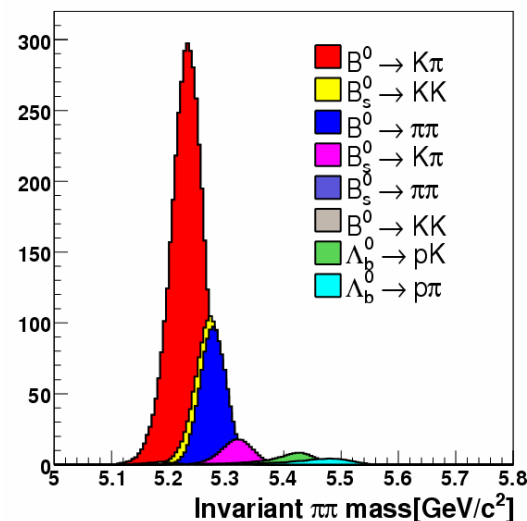
$$B^0/B_s^0 \rightarrow h^+ h'^-$$

CDF Run II Preliminary  $L_{\text{int}} = 1 \text{ fb}^{-1}$



Blue curve in the fit is a 1-dim binned fit (mass region of rare modes excluded by the fit).

CDF Run II Monte Carlo



Despite excellent mass resolution ( $\approx 22 \text{ MeV}/c^2$ ), modes overlap an unresolved peak, and PID resolution is insufficient for event-by-event separation. Hence, fit signal composition with a **Likelihood** that combines information from **kinematics** (mass and momenta) and **particle ID** (dE/dx).

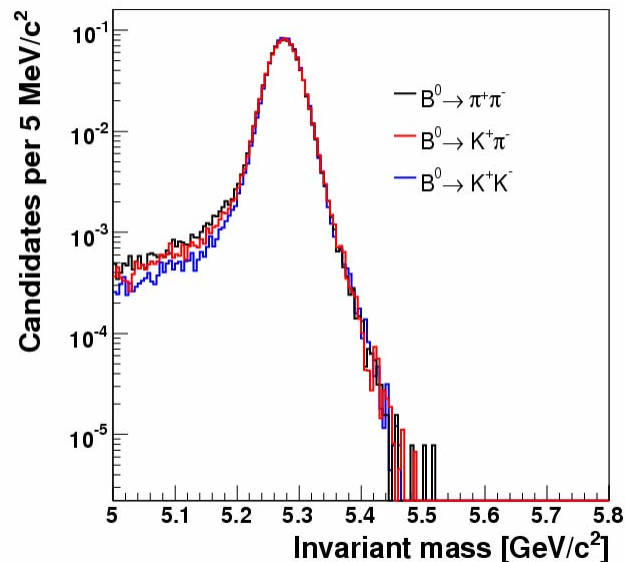
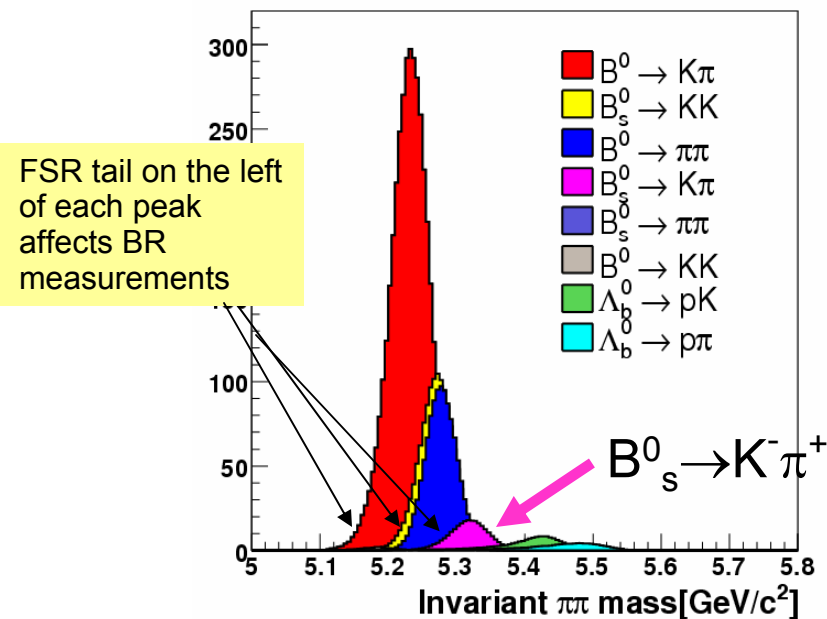


# Peak composition handle 1: invariant mass

BRs measurements are sensitive to the detailed shape of the mass resolution function: **radiative tails** and **non-gaussian tails**  $\Rightarrow$  **need careful parameterization of all resolution effect** because the knowledge of mass resolution is crucial to observe rare mode like  $B^0_s \rightarrow K^- \pi^+$ .

Used the QED calculation from [Baracchini, Isidori Phys.Lett B633:309-313,2006] for  $B(D) \rightarrow \pi\pi/K\pi/KK$  mass resolution templates.

CDF Run II Monte Carlo



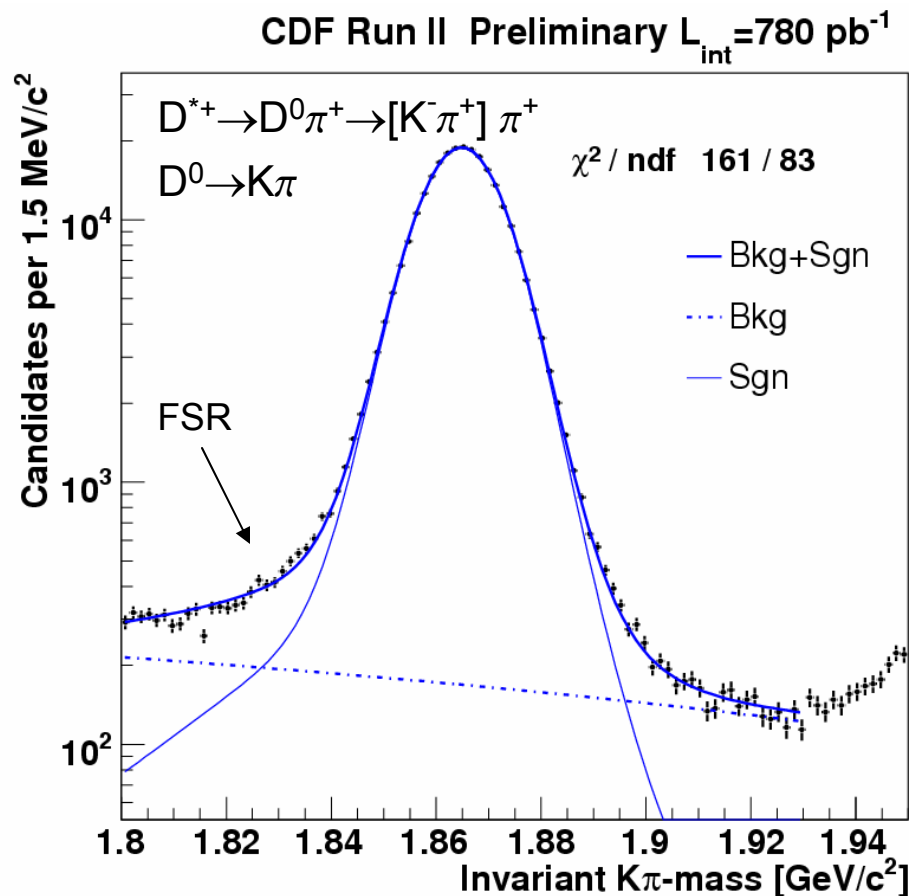


# Mass parameterization

Huge sample of  $D^0 \rightarrow K\pi$  allows an accurate test of our mass resolution model.

We parameterized the mass resolution template for  $D^0 \rightarrow K^- \pi^+$  decays in the same way of  $B \rightarrow hh$  decays and we checked that the model reproduces well the mass line shape of DATA.

**Blue line (Bkg+Sgn)** is 1-dim binned fit where the signal mass line shape is fixed by the model. We fitted only the background parameters.





# Peak composition handle 2: momenta

Kinematics likelihood variables:

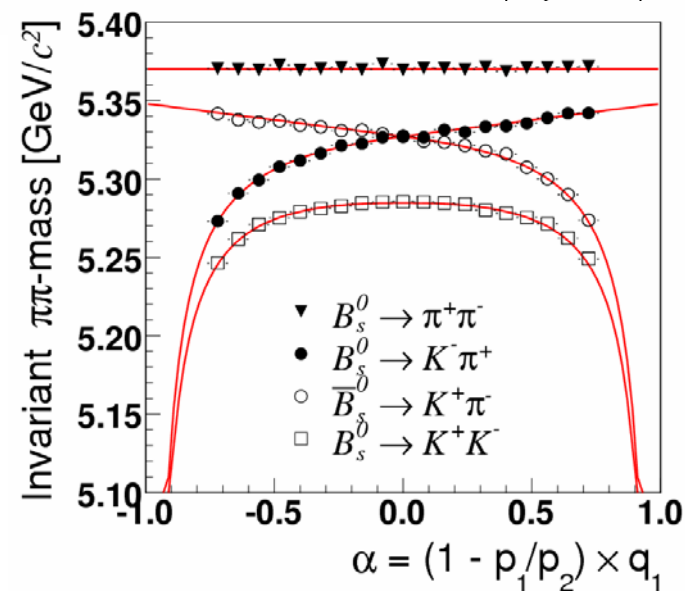
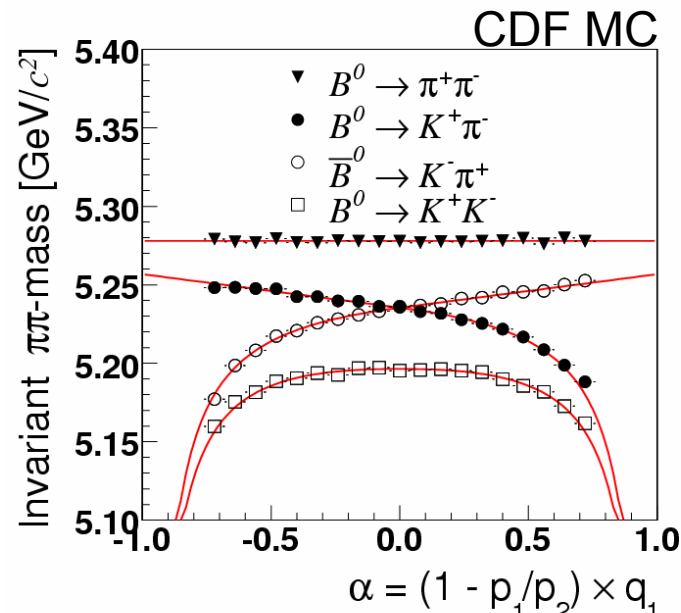
$M_{\pi\pi}$  invariant  $\pi\pi$ -mass

$\alpha = (1 - p_{\min}/p_{\max})q_{\min}$  signed momentum imbalance

$p_{\text{tot}} = p_{\min} + p_{\max}$  scalar sum of 3D momenta

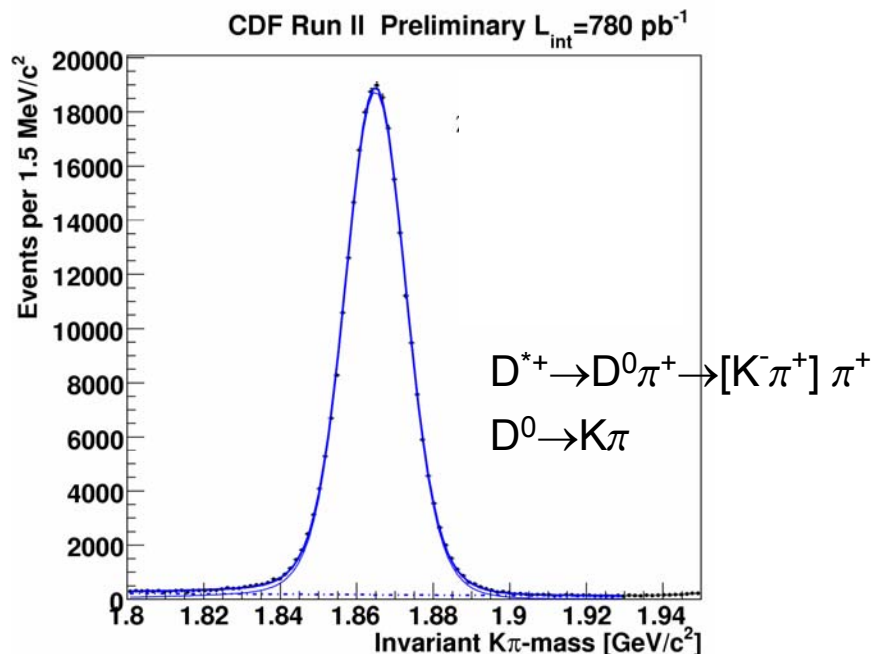
$p_{\min}$  ( $p_{\max}$ ) is the 3D track momentum  
with  $p_{\min} < p_{\max}$

Kinematics discriminates among modes  
(and among self-tagging modes  $K^+\pi^- / K^-\pi^+$ )



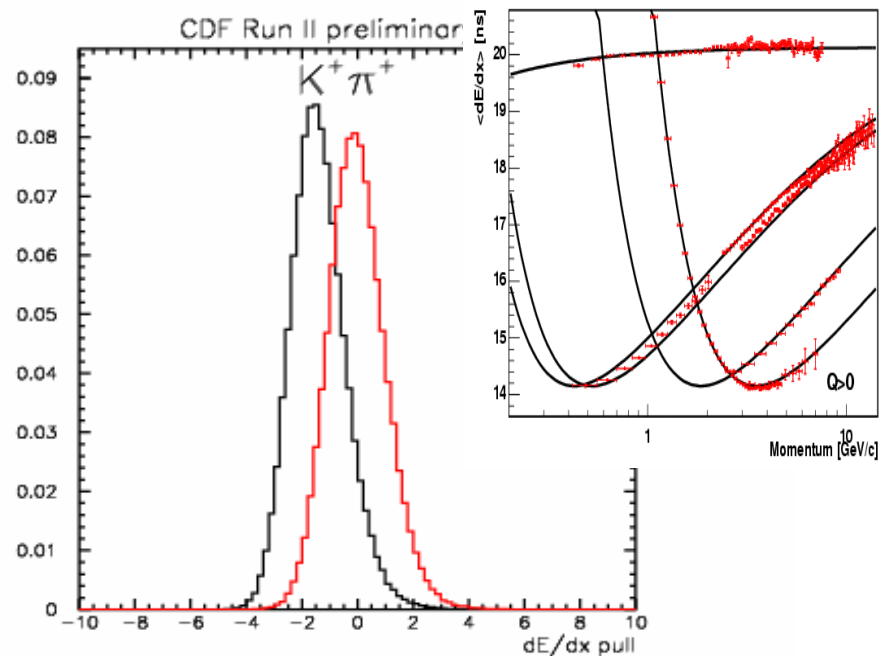


# Peak composition handle 3: dE/dx



~95% pure K and  $\pi$  samples from  
 ~1.5M decays:  $D^{*+} \rightarrow D^0 \pi^+ \rightarrow [K^- \pi^+] \pi^+$

Strong  $D^{*+}$  decay tags the  $D^0$   
 flavor. dE/dx accurately calibrated  
 over tracking volume and time.

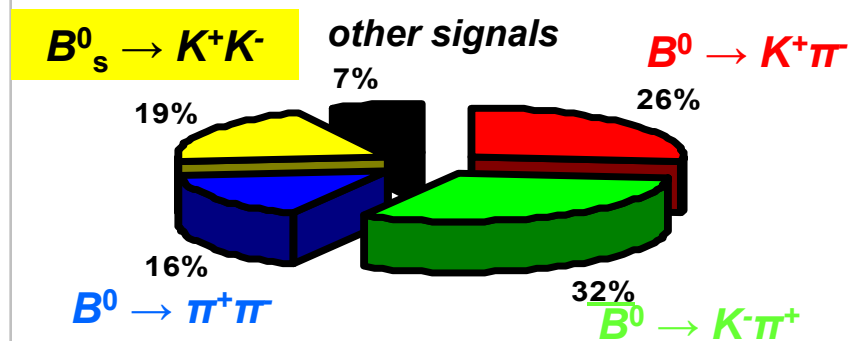


(1.4 $\sigma$  K/ $\pi$  separation at  $p > 2 \text{ GeV}$ )  
 achieve a statistical uncertainty  
 on separating classes of particles  
 which is only 60% worse than  
 one would obtain with completely  
 separated PID distributions.



# “Raw” direct CP asymmetry $B^0 \rightarrow K^+ \pi^-$

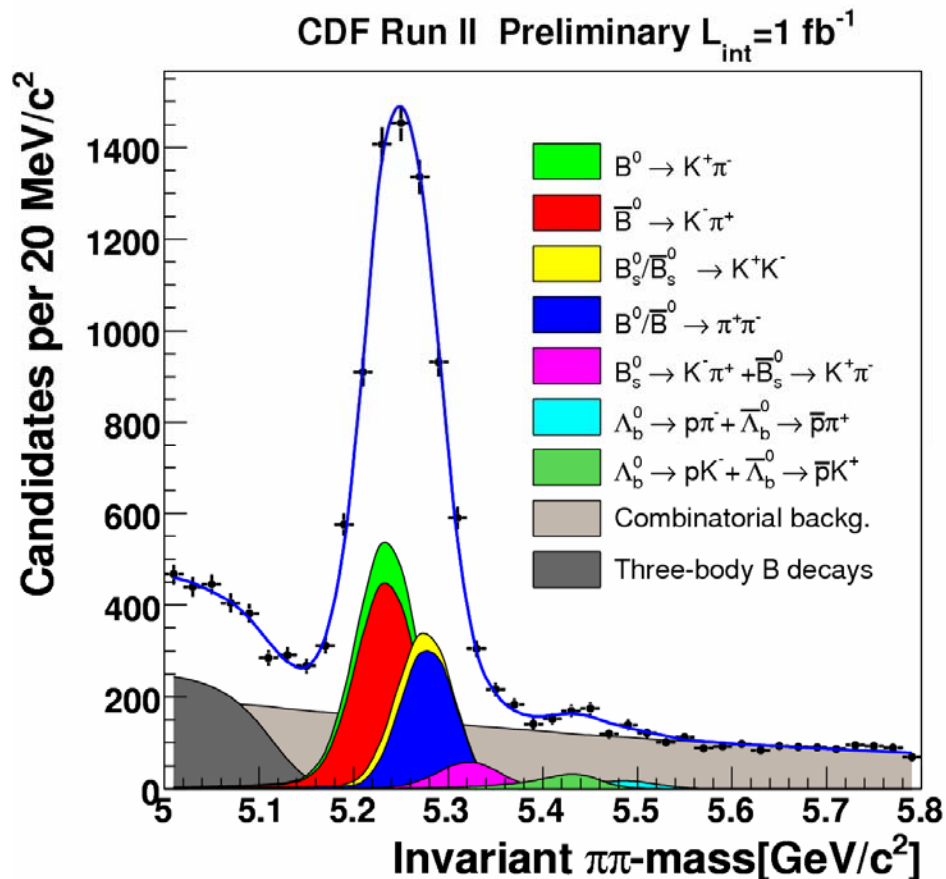
## Uncorrected fractions



parameter	fraction	yield
$B^0 \rightarrow \pi^+ \pi^- + \text{c.c.}$	$(0.160 \pm 0.009)$	$1121 \pm 63$
$B^0 \rightarrow K^+ \pi^- + \text{c.c.}$	$(0.577 \pm 0.010)$	$4045 \pm 84$
$B_s^0 \rightarrow K^+ K^- + \text{c.c.}$	$(0.186 \pm 0.009)$	$1307 \pm 64$

$B^0 \rightarrow h^+ h'^-$  yield like B-factories and  
**unique large sample of  $B_s^0 \rightarrow h^+ h'^-$**

$$A_{\text{CP}} \Big|_{\text{raw}} = \frac{N_{\text{raw}}(\bar{B}^0 \rightarrow K^- \pi^+) - N_{\text{raw}}(B^0 \rightarrow K^+ \pi^-)}{N_{\text{raw}}(\bar{B}^0 \rightarrow K^- \pi^+) + N_{\text{raw}}(B^0 \rightarrow K^+ \pi^-)} = -0.092 \pm 0.023$$





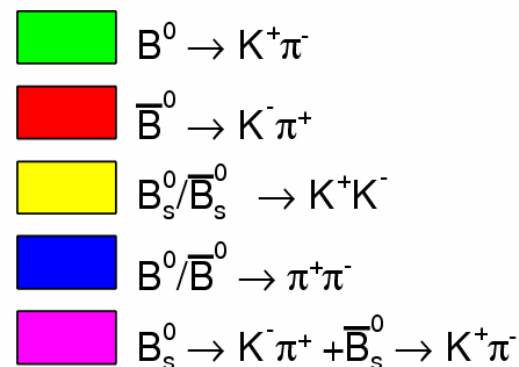
# Fit projections onto PID variables

To separate signals need all information. The  $dE/dx$  works where the kinematics fails (i.e.  $B^0 \rightarrow \pi^+\pi^-$  vs  $B^0_s \rightarrow K^+K^-$ ).

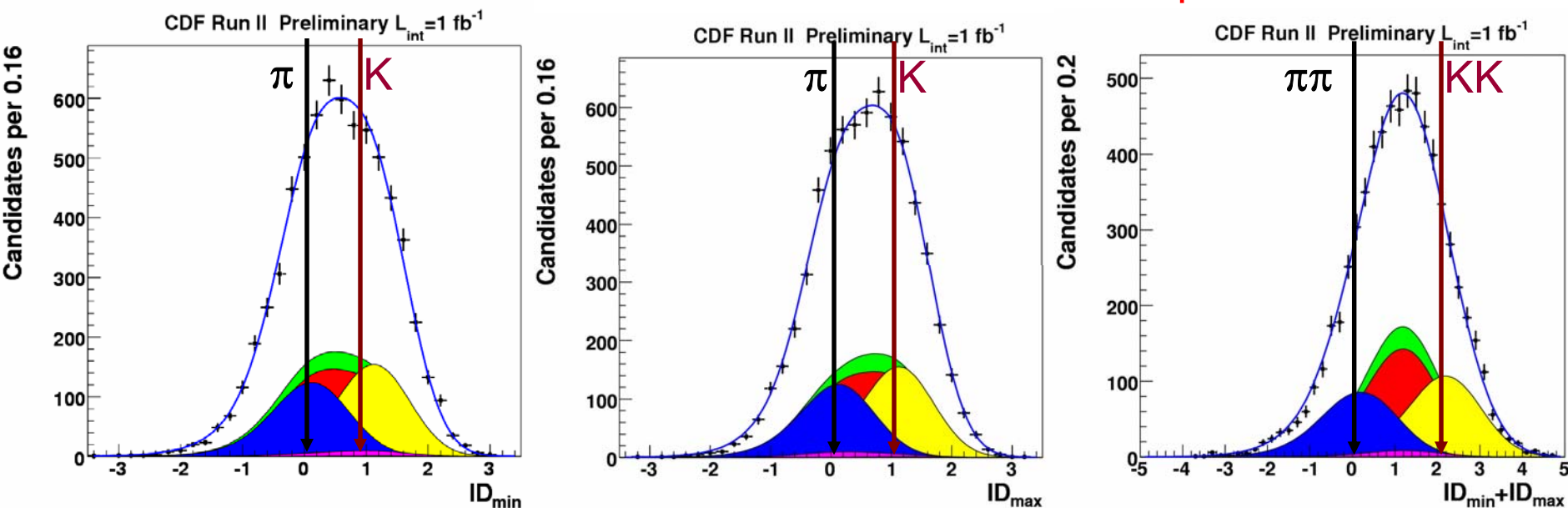
$$ID(track) = \frac{\left. \frac{dE}{dx} \right|_{\text{meas}}(track) - \left. \frac{dE}{dx} \right|_{\text{exp}-\pi}(track)}{\left. \frac{dE}{dx} \right|_{\text{exp}-K}(track) - \left. \frac{dE}{dx} \right|_{\text{exp}-\pi}(track)}.$$

$\langle ID \rangle(\text{pion hypothesis}) = 0$

$\langle ID \rangle(\text{kaon hypothesis}) = 1$



PID separation  $\pi\pi/KK \cong 2\sigma$





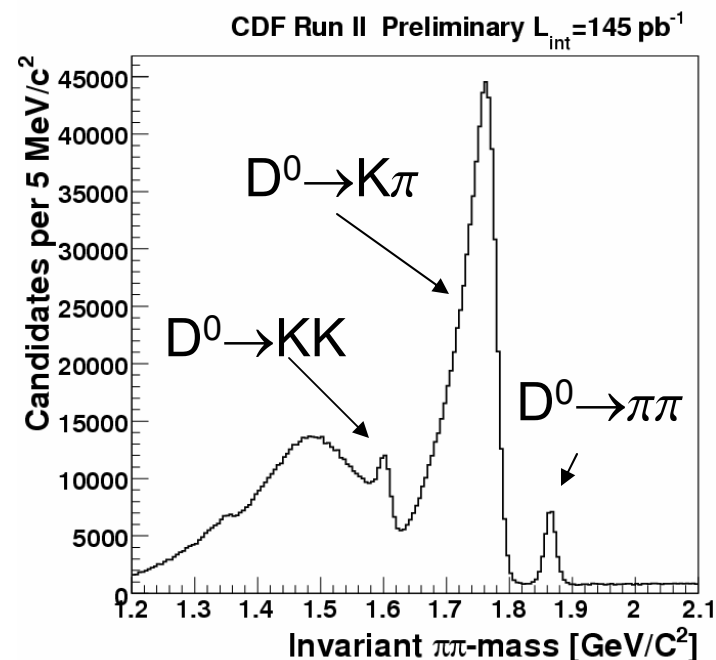
# $A_{CP}$ correction

$$A_{CP}(B^0 \rightarrow K^+ \pi^-) = \frac{N_{\text{raw}}(\bar{B}^0 \rightarrow K^- \pi^+) \cdot \frac{\epsilon(K^+ \pi^-)}{\epsilon(K^- \pi^+)} - N_{\text{raw}}(B^0 \rightarrow K^+ \pi^-)}{N_{\text{raw}}(\bar{B}^0 \rightarrow K^- \pi^+) \cdot \frac{\epsilon(K^+ \pi^-)}{\epsilon(K^- \pi^+)} + N_{\text{raw}}(B^0 \rightarrow K^+ \pi^-)}$$

Only the different  $K^+/K^-$  interaction rate with material matters.  $K^-$  has a larger hadronic cross section than  $K^+$ . Small ( $\sim 0.6\%$ ) correction is applied to the “raw” yield results to convert it into a measurement

CDF has an huge sample of prompt  $D^0 \rightarrow h^+ h^-$  corresponding about 15M in  $1\text{fb}^{-1}$ . Using the same  $B \rightarrow hh$  fit technology and the assumption that the direct  $A_{CP}(D^0 \rightarrow K\pi) \cong 0$  (SM)  $\Rightarrow$  measurement from the DATA of the efficiency ratio  $\epsilon(K^- \pi^+)/\epsilon(K^+ \pi^-)$ :

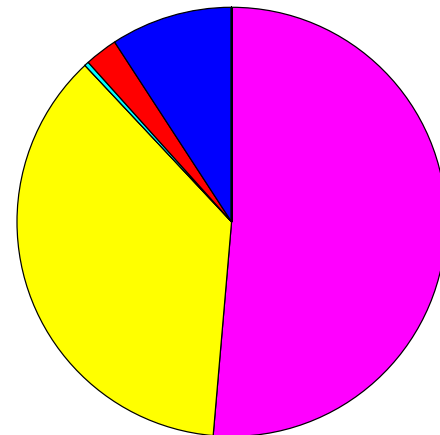
$$\frac{\epsilon(K^+ \pi^-)}{\epsilon(K^- \pi^+)} = 1.0131 \pm 0.0028 \text{ (stat.)}.$$





# Systematics $A_{CP}(B^0 \rightarrow K^+ \pi^-)$

- dE/dx model ( $\pm 0.0064$ );
- nominal  $B$ -meson masses input to the fit ( $\pm 0.005$ );
- global scale of masses;
- charge-asymmetries ( $\pm 0.001$ );
- combinatorial background model ( $\pm 0.003$ ).



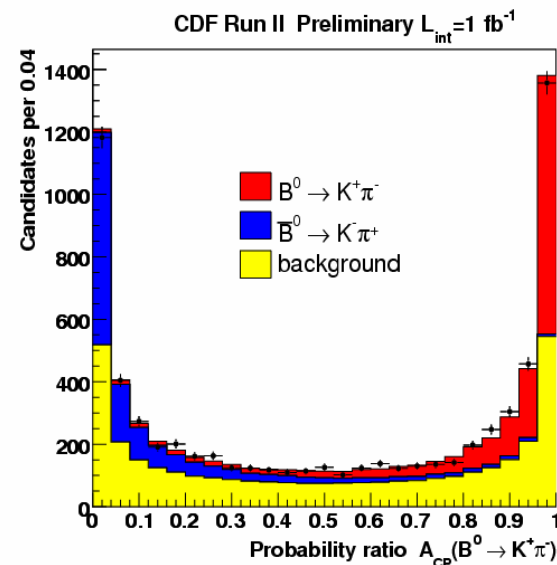
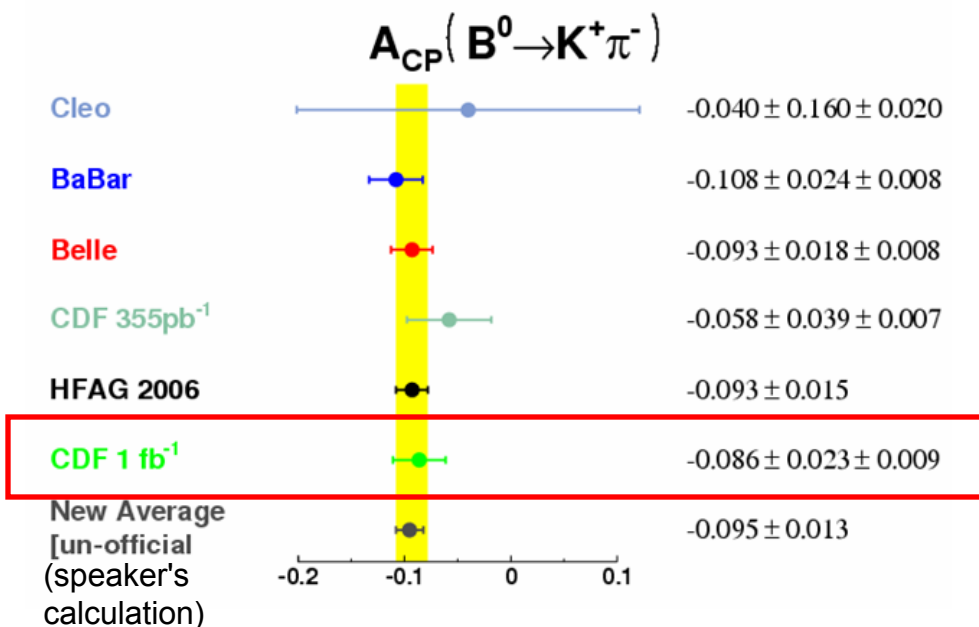
Total systematic uncertainty is 0.9%, smaller than the 2.3% statistical uncertainty. Although the accurate dE/dx calibration/parameterization uses the huge data sample of tagged  $D^0 \rightarrow K^- \pi^+$  the dominant systematics is due to the dE/dx.

dE/dx systematics checks: measurement of the direct  $A_{CP}(D^0 \rightarrow K\pi)$  with two fits : **kinematic-only** and **dE/dx-only**. The discrepancy of two fits ( $\cong 0.006$ ) is within the quoted systematics.



# Direct CP asymmetry $B^0 \rightarrow K^+ \pi^-$

$$A_{CP} = \frac{N(\bar{B}^0 \rightarrow K^- \pi^+) - N(B^0 \rightarrow K^+ \pi^-)}{N(\bar{B}^0 \rightarrow K^- \pi^+) + N(B^0 \rightarrow K^+ \pi^-)} = -0.086 \pm 0.023 \text{ (stat.)} \pm 0.009 \text{ (syst.)}$$



CDF is becoming a major player in the CPV game. The CDF results is the second world's best measurement.

In agreement with the current HFAG world average (calculated with our previous result on 355 pb<sup>-1</sup>). **The significance moved from 6σ to 7σ.**



# BRs: $B^0 \rightarrow \pi^+\pi^-$ and $B^0_s \rightarrow K^+K^-$

CDF Run II Preliminary  $L_{\text{int}} = 1 \text{ fb}^{-1}$

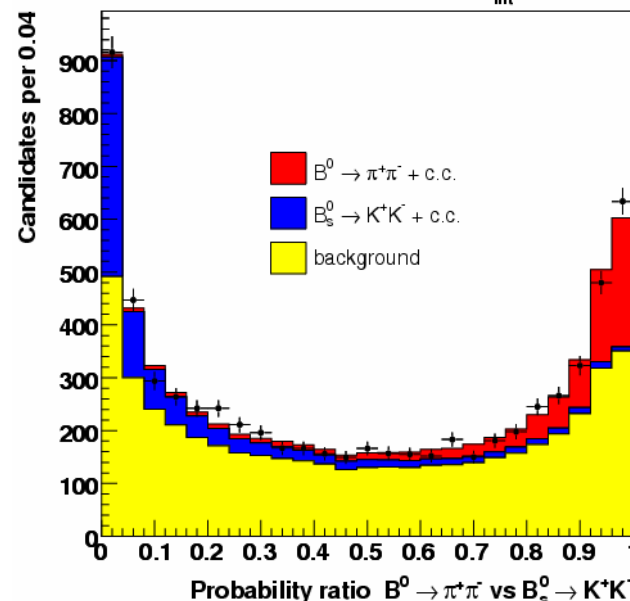
$$\frac{f_s \cdot BR(B_s^0 \rightarrow K^+K^-)}{f_d \cdot BR(B^0 \rightarrow K^+\pi^-)} = 0.324 \pm 0.019 (\text{stat.}) \pm 0.041 (\text{syst.})$$

$$\frac{BR(B^0 \rightarrow \pi^+\pi^-)}{BR(B^0 \rightarrow K^+\pi^-)} = 0.259 \pm 0.017 (\text{stat.}) \pm 0.016 (\text{syst.})$$

using HFAG:

$$BR(B_s^0 \rightarrow K^+K^-) = (24.4 \pm 1.4 (\text{stat.}) \pm 4.6 (\text{syst.})) \times 10^{-6}$$

$$BR(B^0 \rightarrow \pi^+\pi^-) = (5.10 \pm 0.33 (\text{stat.}) \pm 0.36 (\text{syst.})) \times 10^{-6}$$



$BR(B_s^0 \rightarrow K^+K^-)$  and  $BR(B^0 \rightarrow \pi^+\pi^-)$  are becoming high precision measurement. Conservative systematics for  $BR(B_s^0 \rightarrow K^+K^-)$  but soon systematics  $\cong$  statistics.

Theoretical expectations are not completely in agreement.

[Matias et al. PRL97, 061801, 2006]  $BR(B_s^0 \rightarrow K^+K^-) / BR(B^0 \rightarrow K^+\pi^-) \cong 1$

[Khodjamirian et al. PRD68:114007, 2003] predict large SU(3) breaking  $\cong 2$ .

CDF measurement disfavors predictions of large breaking.



$$B^0_s \rightarrow K^- \pi^+, B^0_s \rightarrow \pi^+ \pi^-, B^0 \rightarrow K^+ K^-$$

and

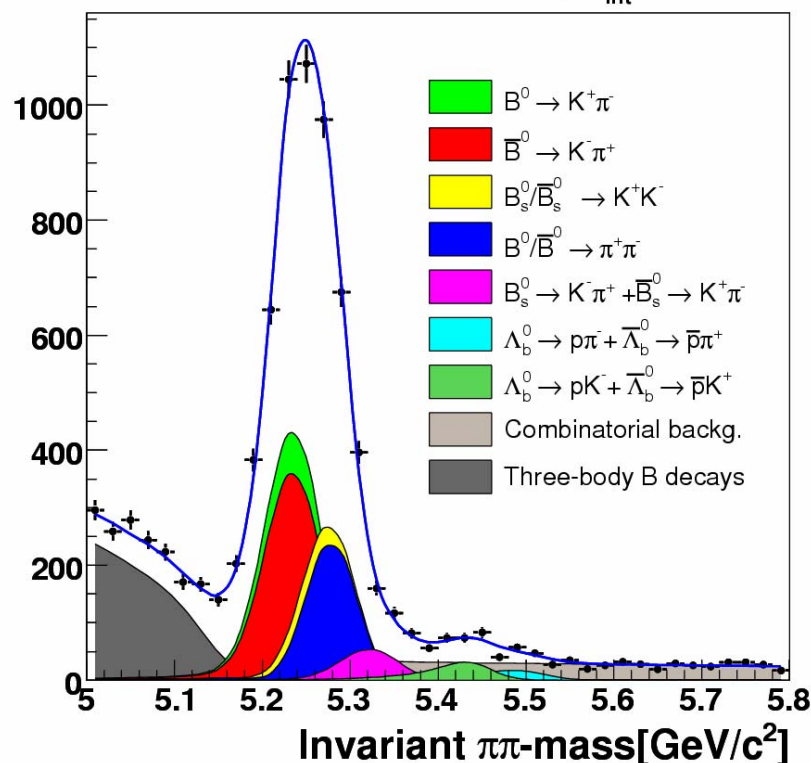
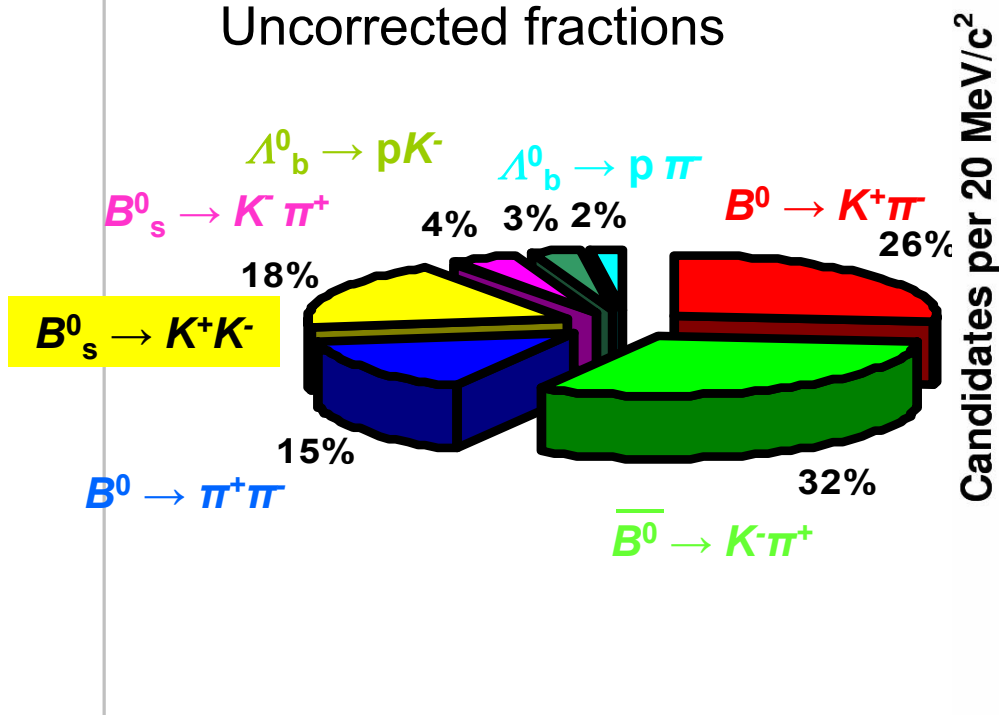
$$\Lambda^0_b \rightarrow p \pi^-, \Lambda^0_b \rightarrow p K^-$$



# Rare modes search (tight cuts)

CDF Run II Preliminary  $\mathcal{L}_{\text{int}} = 1 \text{ fb}^{-1}$

Uncorrected fractions



## New rare modes observed



$$N_{\text{raw}}(B_s^0 \rightarrow K^- \pi^+) = 230 \pm 34 \text{ (stat.)} \pm 16 \text{ (syst.)} \quad (8\sigma)$$

$$N_{\text{raw}}(\Lambda_b^0 \rightarrow p \pi^-) = 110 \pm 18 \text{ (stat.)} \pm 16 \text{ (syst.)} \quad (6\sigma)$$

$$N_{\text{raw}}(\Lambda_b^0 \rightarrow p K^-) = 156 \pm 20 \text{ (stat.)} \pm 11 \text{ (syst.)} \quad (11\sigma)$$



$$B_s^0 \rightarrow K^- \pi^+$$

## First observation

$$N_{\text{raw}}(B_s^0 \rightarrow K^- \pi^+) = 230 \pm 34 \text{ (stat.)} \pm 16 \text{ (syst.)}$$

$$\frac{f_s \cdot BR(B_s^0 \rightarrow K^- \pi^+)}{f_d \cdot BR(B^0 \rightarrow K^+ \pi^-)} = 0.066 \pm 0.010 \text{ (stat.)} \pm 0.010 \text{ (syst.)}$$

using HFAG:

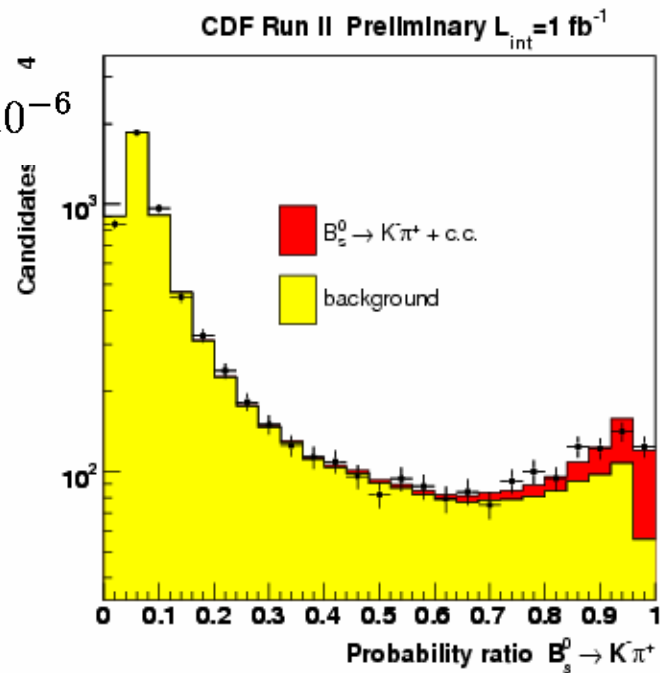
$$BR(B_s^0 \rightarrow K^- \pi^+) = (5.0 \pm 0.75 \text{ (stat.)} \pm 1.0 \text{ (syst.)}) \times 10^{-6}$$

[Beneke&Neubert NP B675, 333(2003)]:  $\cong [7-10] \cdot 10^{-6}$

[Yu, Li, Yu, PRD71: 074026 (2005)]:  $\cong [6-10] \cdot 10^{-6}$

[Williamson, Zupan. PRD74 (2006) 014003]:  $\cong 4.9 \cdot 10^{-6}$

**Significance including statistic and systematic error is equal to  $8\sigma$ .**





# Direct CP asymmetry $B_s^0 \rightarrow K^- \pi^+$

Large SM expectation for this asymmetry  $\cong 0.37$  (calculated with new measured BR).

$$A_{CP} = \frac{N(\bar{B}_s^0 \rightarrow K^+ \pi^-) - N(B_s^0 \rightarrow K^- \pi^+)}{N(\bar{B}_s^0 \rightarrow K^+ \pi^-) + N(B_s^0 \rightarrow K^- \pi^+)} = 0.39 \pm 0.15 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$$

**Asymmetry 2.5  $\sigma$**

Compare rates and asymmetries of  $B^0 \rightarrow K^+ \pi^-$  and  $B_s^0 \rightarrow K^- \pi^+$  unique to CDF – to probe NP with minimal assumption, just SM. [Lipkin, Phys. Lett. B621:126, .2005],[Gronau Rosner Phys.Rev. D71 (2005) 074019]. SM predicts that:

$$|A(B_s \rightarrow \pi^+ K^-)|^2 - |A(\bar{B}_s \rightarrow \pi^- K^+)|^2 = |A(\bar{B}_d \rightarrow \pi^+ K^-)|^2 - |A(B_d \rightarrow \pi^- K^+)|^2$$

using HFAG:

$$\frac{|A(\bar{B}_d \rightarrow \pi^+ K^-)|^2 - |A(B_d \rightarrow \pi^- K^+)|^2}{|A(B_s \rightarrow \pi^+ K^-)|^2 - |A(\bar{B}_s \rightarrow \pi^- K^+)|^2} = 0.84 \pm 0.42(\text{stat.}) \pm 0.15(\text{syst.}) \text{ (=1 SM)}$$



# Upper limits: $B_s^0 \rightarrow \pi^+ \pi^-$ and $B^0 \rightarrow K^+ K^-$

$$\frac{f_s \cdot BR(B_s^0 \rightarrow \pi^+ \pi^-)}{f_d \cdot BR(B^0 \rightarrow K^+ \pi^-)} = 0.007 \pm 0.004 \text{ (stat.)} \pm 0.005 \text{ (syst.)} \quad 1.5 \sigma$$

$$\frac{BR(B^0 \rightarrow K^+ K^-)}{BR(B^0 \rightarrow K^+ \pi^-)} = 0.020 \pm 0.008 \text{ (stat.)} \pm 0.006 \text{ (syst.)} \quad 1.5 \sigma$$

using HFAG:

$$BR(B^0 \rightarrow K^+ K^-) = (0.39 \pm 0.16 \text{ (stat.)} \pm 0.12 \text{ (syst.)}) \times 10^{-6} \quad (< 0.7 \cdot 10^{-6} \text{ @ 90\% C.L.})$$

Expected  $[0.01 - 0.2] \cdot 10^{-6}$  [Beneke&Neubert NP B675, 333(2003)]

$$BR(B_s^0 \rightarrow \pi^+ \pi^-) = (0.53 \pm 0.31 \text{ (stat.)} \pm 0.40 \text{ (syst.)}) \times 10^{-6} \quad (< 1.36 \cdot 10^{-6} \text{ @ 90\% C.L.})$$

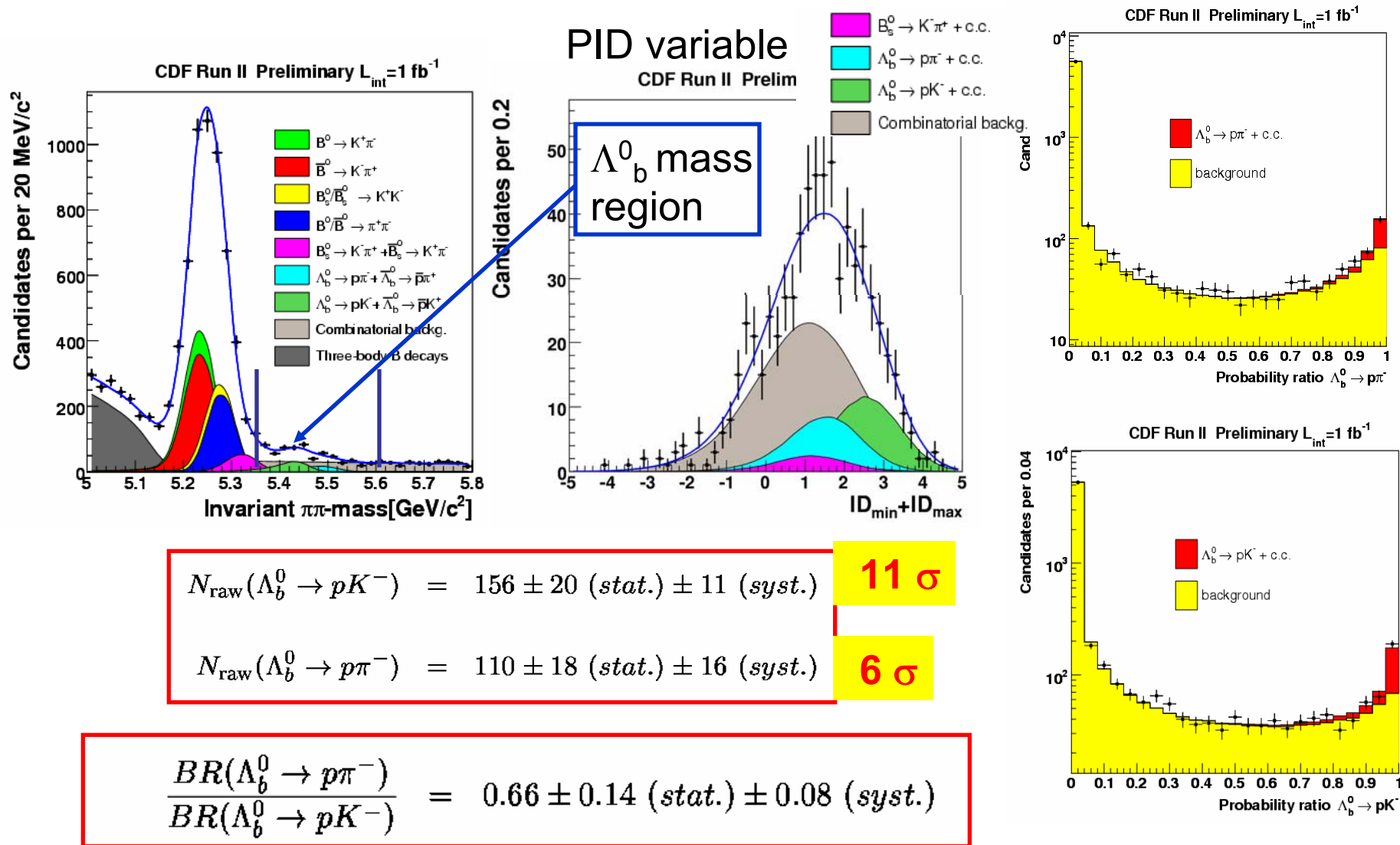
Expected:  $[0.007 - 0.08] \cdot 10^{-6}$  [Beneke&Neuber t NP B675, 333(2003)]

Expected:  $0.42 \pm 0.06$  [Ying Li et al. hep-ph/0404028]

**World's best upper limits for  $B_s^0 \rightarrow \pi^+ \pi^-$  while same resolution of B-factories for  $B^0 \rightarrow K^+ K^-$ .** Both modes are annihilation-dominated decays and no observed yet them – they are hard to predict exactly.



# First observation $\Lambda_b^0 \rightarrow p\pi^-$ and $\Lambda_b^0 \rightarrow pK^-$





# Conclusions

- **First observation** of  $B^0_s \rightarrow K^- \pi^+$  mode
- **First observation** of baryon charmless modes:  $\Lambda_b \rightarrow pK$  and  $\Lambda_b \rightarrow p\pi$
- **First measurement of direct CPV in  $B^0_s$** :  $A_{CP}(B^0_s \rightarrow K^- \pi^+)$  in agreement with SM predictions ( $2.5\sigma$  from 0)
- Precision  $A_{CP}(B^0 \rightarrow K^+ \pi^-)$  confirm B-factories results, comparable accuracy. Significance of direct-CPV now  $>7\sigma$ .
- Updated measurement of  $BR(B^0_s \rightarrow K^+ K^-)$  disfavors expectations of large U-spin breaking
- New measurement of  $BR(B^0 \rightarrow K^+ K^-)$ , accuracy as at  $e^+e^-$  B-factories
- New upper-limit on annihilation mode  $B^0_s \rightarrow \pi^+ \pi^-$

CDF is now a major player in Charmless two-body decays of the  $B^0$ , plus has unique results on  $B^0_s$  and baryons. Coming up: much more data and more measurements (including time-dependent).



backup



# The Tevatron $p\bar{p}$ collider

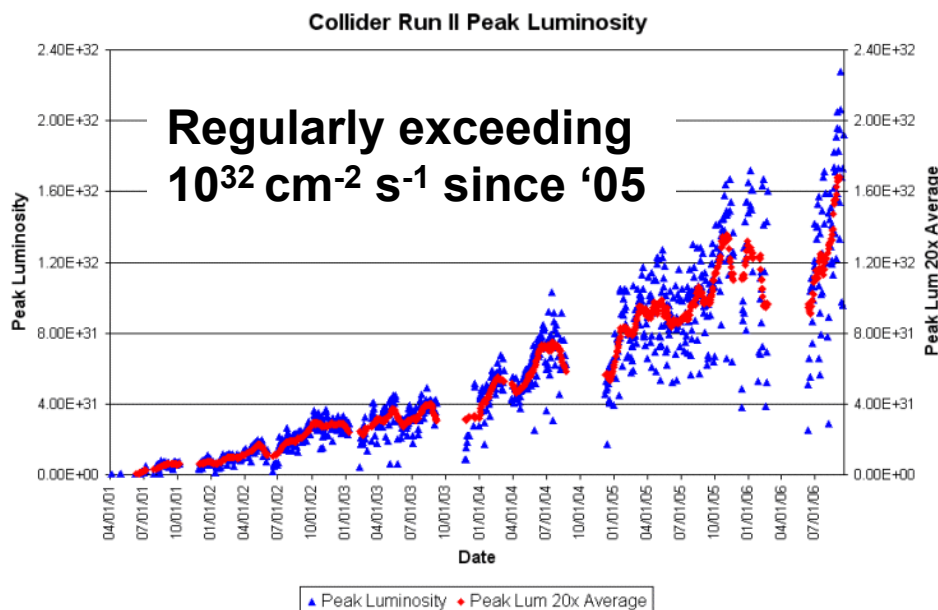
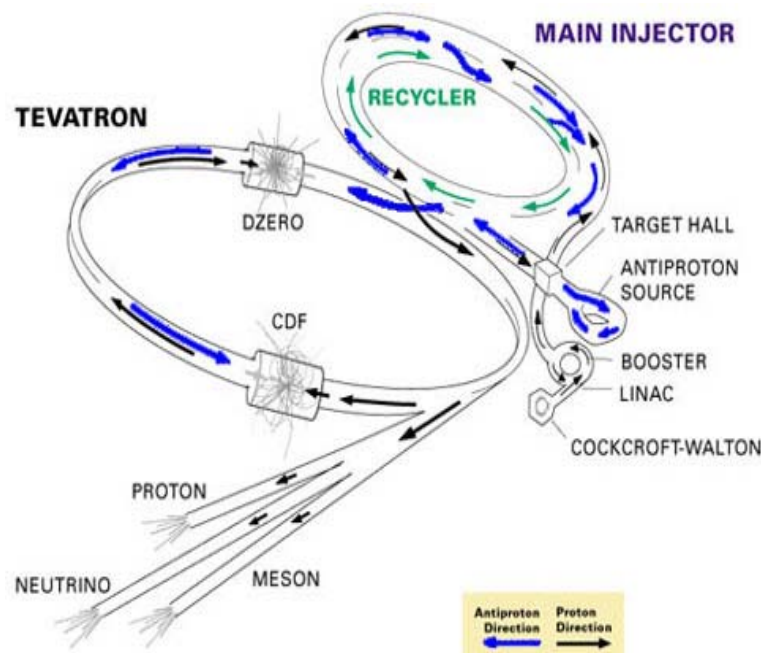
36 (proton)  $\times$  36 (antiproton) bunches  
X-ing time 396 ns at  $\sqrt{s} = 1.96$  TeV

record peak is  $L = 2.37 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$

$\sim 20 \text{ pb}^{-1} / \text{week}$  recorded on tape

# of interactions per bunch-crossing:

$\langle N \rangle_{\text{poisson}} = 2$  (at  $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ )



$L_{\text{int}} \sim 1.5 \text{ fb}^{-1}$  on tape  
( $\sim 1 \text{ fb}^{-1}$  for analysis)

Stable data taking efficiency:  $> 85\%$ .  
Results here use  $\sim 1 \text{ fb}^{-1}$



# The CDF II detector

## 7 to 8 silicon layers

$1.6 < r < 28$  cm,  $|z| < 45$  cm  
 $|\eta| \leq 2.0$   $\sigma(\text{hit}) \sim 15$   $\mu\text{m}$

Some resolutions:

$p_T \sim 0.15\%$   $p_T$  (c/GeV)

$J/\psi$  mass  $\sim 14$  MeV

EM  $E \sim 16\%/\sqrt{E}$

Had  $E \sim 80\%/\sqrt{E}$

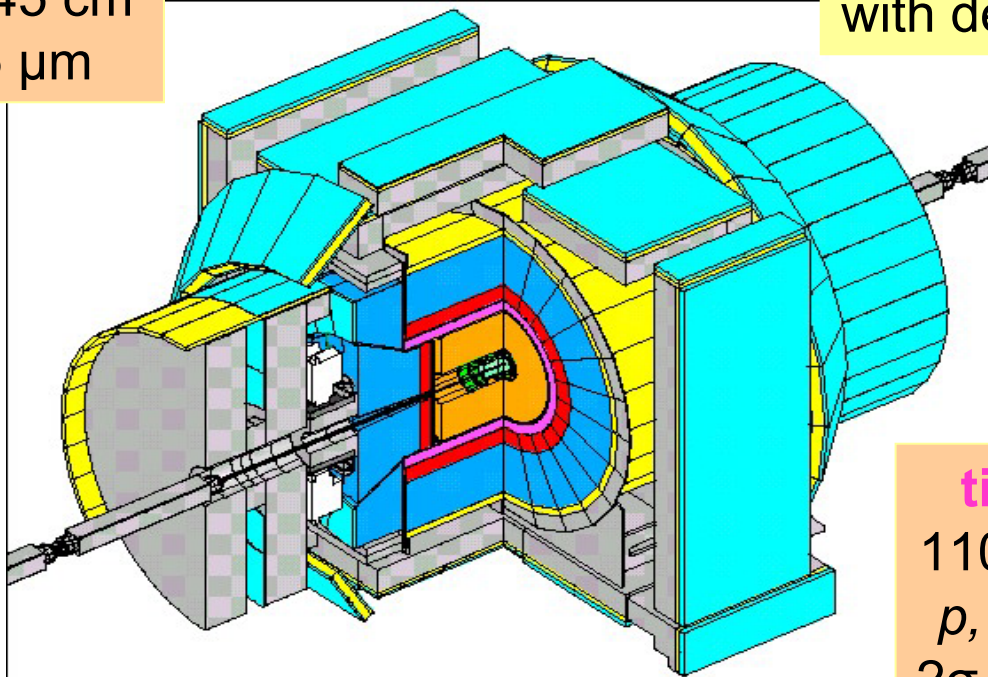
$d_0 \sim 40$   $\mu\text{m}$

(includes beam spot)

## 1.4 T magnetic field

Lever arm 132 cm

132 ns front end  
chamber tracks at L1  
silicon tracks at L2  
25000 / 300 / 100 Hz  
with dead time  $< 5\%$



## time-of-flight

110 ps at 150 cm  
 $p$ ,  $K$ ,  $\pi$  identific.  
 $2\sigma$  at  $p_T < 1.6$  GeV

## 96 layer drift chamber $|\eta| \leq 1.0$

$44 < r < 132$  cm,  $|z| < 155$  cm

30k channels,  $\sigma(\text{hit}) \sim 140$   $\mu\text{m}$

$dE/dx$  for  $p$ ,  $K$ ,  $\pi$  identification

## scintillator and tile/fiber sampling calorimetry

$|\eta| < 3.64$

## $\mu$ coverage

$|\eta| \leq 1.5$

84% in  $\phi$



# Heavy Flavor physics at the Tevatron

## The Good

$b\bar{b}$  production x-section  $O(10^5)$  larger than  $e^+e^-$  at  $\Upsilon(4S)/Z^0$ . Incoherent strong production of all  $b$ -hadrons:  $B^+$ ,  $B^0$ ,  $B_s^0$ ,  $B_c$ ,  $\Lambda_b$ ,  $\Xi_b$  ...

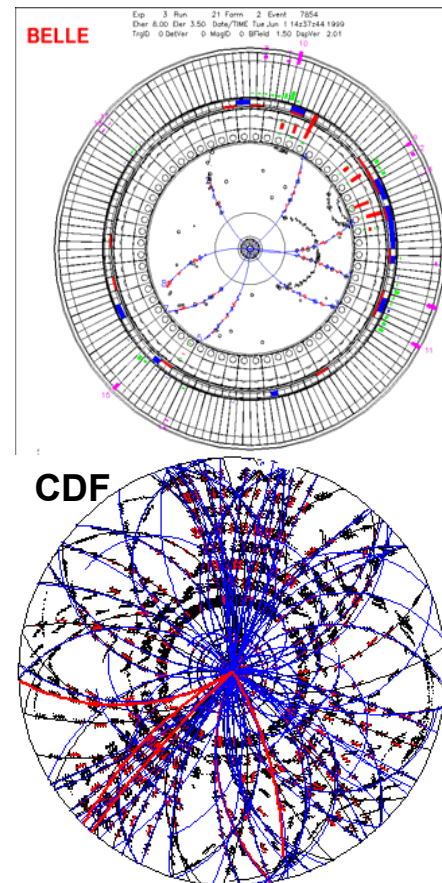
## The Bad

Total inelastic x-section  $\times 10^3$  larger than  $\sigma(b\bar{b})$ . BRs' for interesting processes  $O(10^{-6})$ .

## ...and The Ugly

Messy environments with large combinatorics.

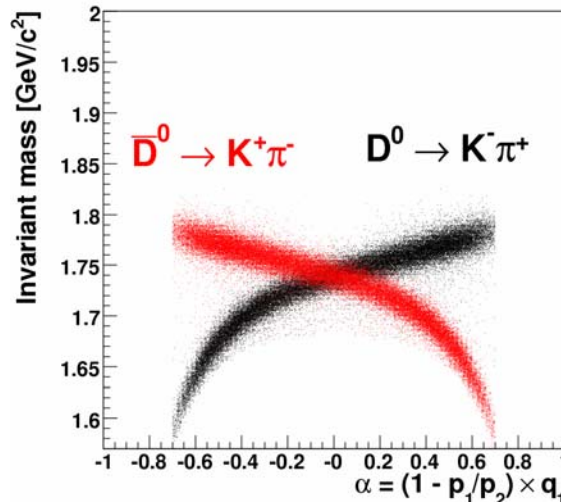
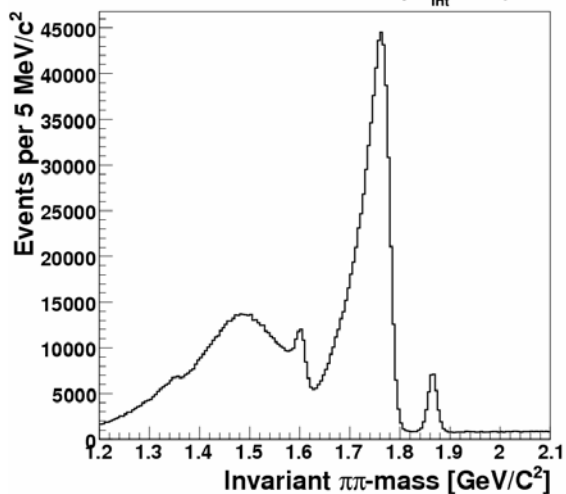
Need highly selective trigger



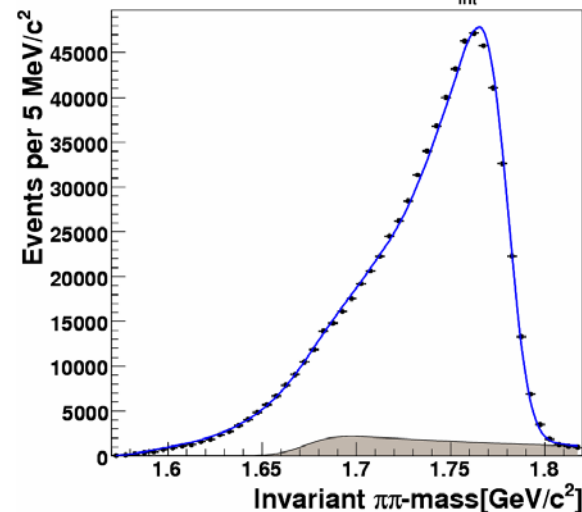


# $\epsilon(K^+\pi^-)/\epsilon(K^-\pi^+)$ from $D^0 \rightarrow K^-\pi^+$

CDF Run II Preliminary  $L_{\text{int}}=145 \text{ pb}^{-1}$



CDF Run II Preliminary  $L_{\text{int}}=145 \text{ pb}^{-1}$



With  $\epsilon(K^+\pi^-)/\epsilon(K^-\pi^+)$  from MC we obtain:

$$A_{\text{CP}} = \frac{N_{\text{raw}}(\bar{D}^0 \rightarrow K^+\pi^-) \cdot \frac{\epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-)} - N_{\text{raw}}(D^0 \rightarrow K^-\pi^+)}{N_{\text{raw}}(\bar{D}^0 \rightarrow K^+\pi^-) \cdot \frac{\epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-)} + N_{\text{raw}}(D^0 \rightarrow K^-\pi^+)} = -0.00059 \pm 0.00136 \text{ (stat.)} \pm 0.0022 \text{ (syst.)}. \quad (22)$$

if we assume the  $A_{\text{CP}}(D^0 \rightarrow K^-\pi^+) = 0$ , we obtain from DATA:

$$\frac{\epsilon(K^-\pi^+)}{\epsilon(K^+\pi^-)} = 0.9837 \pm 0.0027 \text{ (stat.)}$$



## Cross-check of $D^0 \rightarrow K\pi$ asymmetry with $dE/dx$

To check the  $dE/dx$  systematics we performed an  $A_{CP}$  fit on a  $D^0 \rightarrow K\pi$  sample. We did two fits : **kinematic-only** and  **$dE/dx$ -only**.

### Kinematic-only

$$\frac{N_{\text{raw}}(\bar{D}^0 \rightarrow K^+ \pi^-) - N_{\text{raw}}(D^0 \rightarrow K^- \pi^+)}{N_{\text{raw}}(\bar{D}^0 \rightarrow K^+ \pi^-) + N_{\text{raw}}(D^0 \rightarrow K^- \pi^+)} = 0.00823 \pm 0.00136$$

### $dE/dx$ -only

$$\frac{N_{\text{raw}}(\bar{D}^0 \rightarrow K^+ \pi^-) - N_{\text{raw}}(D^0 \rightarrow K^- \pi^+)}{N_{\text{raw}}(\bar{D}^0 \rightarrow K^+ \pi^-) + N_{\text{raw}}(D^0 \rightarrow K^- \pi^+)} = 0.00207 \pm 0.00157$$

In the  $D^0 \rightarrow K\pi$  we obtain  $A_{CP}(\text{kine}) - A_{CP}(dE/dx) = 0.00616$

The discrepancy between the two fits is within our quoted  $dE/dx$  systematics on direct  $A_{CP}(B^0 \rightarrow K\pi)$  : 0.0064.



# Systematics: $A_{CP}(B^0 \rightarrow K^+ \pi^-)$

source	shift wrt central fit
mass scale	0.0004
asymmetric momentum-p.d.f	0.0001
dE/dx	0.0064
input masses	0.0054
combinatorial background model	0.0027
momentum background model	0.0007
MC statistics	—
charge asymmetry	0.0014
$\Delta\Gamma_s/\Gamma_s$ Standard Model	—
lifetime	—
isolation efficiency	—
XFT-bias correction	—
<b>TOTAL (sum in quadrature)</b>	<b>0.009</b>



# Systematics

$$B^0 \rightarrow \pi^+ \pi^- \text{ and } B_s^0 \rightarrow K^+ K^-$$

$$\frac{BR(B^0 \rightarrow \pi^+ \pi^-)}{BR(B^0 \rightarrow K^+ \pi^-)} \quad \frac{f_s \cdot BR(B_s^0 \rightarrow K^+ K^-)}{f_d \cdot BR(B^0 \rightarrow K^+ \pi^-)}$$

source	shift wrt central fit	shift wrt central fit
mass scale	0.0036	0.0034
asymmetric momentum-p.d.f	0.0006	0.0030
dE/dx	0.0129	0.0107
input masses	0.0050	0.0050
combinatorial background model	0.0020	0.0020
momentum background model	0.0010	0.0060
MC statistics	0.0011	0.0012
charge asymmetry	—	—
$\Delta\Gamma_s/\Gamma_s$ Standard Model	—	0.0060
lifetime	—	0.0060
isolation efficiency	—	0.0370
XFT-bias correction	0.0050	0.0080
<b>TOTAL (sum in quadrature)</b>	<b>0.0165</b>	<b>0.0413</b>

Isolation efficiency  
 $\varepsilon(B^0)/\varepsilon(B_s^0)$  from the  
 data using 180 pb<sup>-1</sup>



# Fit of composition

Un-binned ML fit that uses kinematic and PID information from 5 observables

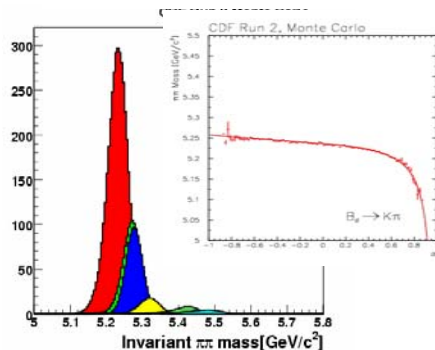
$$\mathcal{L}(\vec{\theta}) = \prod_{i=1}^N \mathcal{L}_i(\vec{\theta})$$

fraction of  $j^{\text{th}}$  mode, to be determined by the fit

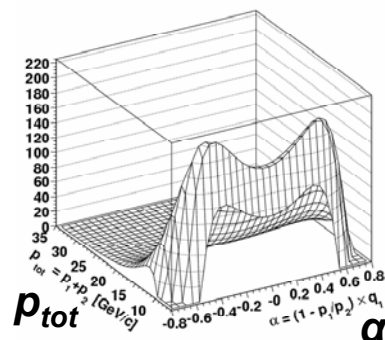
$$\mathcal{L}_i(\vec{\theta}) = (1 - b) \sum f_j \mathcal{L}_j^{\text{sign}} + b \mathcal{L}^{\text{bckg}}$$

$$pdf_j^m(m_{\pi\pi}|\alpha, p_{tot}; \vec{\theta}) \cdot pdf_j^p(\alpha, p_{tot}; \vec{\theta}) \cdot pdf_j^{\text{PID}}(\text{ID}_1, \text{ID}_2|p_{tot}, \alpha; \vec{\theta})$$

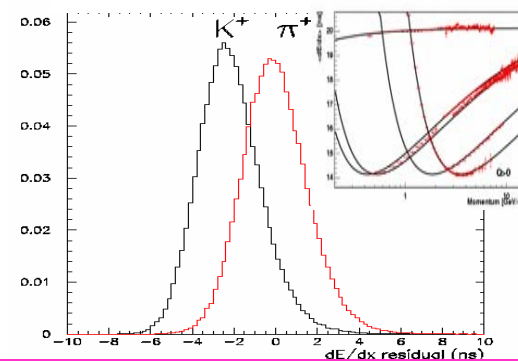
mass term



momentum term



PID term



Signal shapes: from MC and analytic formula  
Background shapes: from data sidebands

sign and bckg shapes  
from  $D^0 \rightarrow K^- \pi^+$



# CDF II at the TeVatron

- TeVatron

- 36 (*proton*)  $\times$  36 (*antiproton*) bunches  
X-ing time 396 ns at  $\sqrt{s} = 1.96$  TeV
- record peak is  $L = 2.37 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
- $\sim 20 \text{ pb}^{-1}$  / week recorded on tape

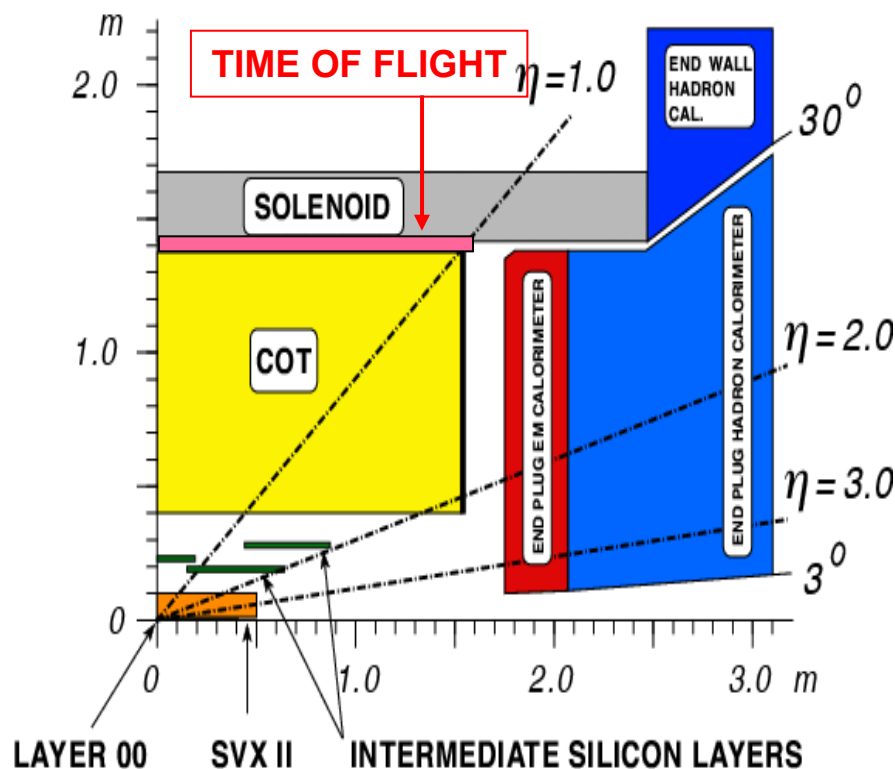
- CDF(Tracking):

- Central Drift chamber 96 layers (COT)  
 $\sigma(P_T)/P_T^2 \sim 0.1\% \text{ GeV}^{-1}$
- PID from  $dE/dx + \text{TOF}$ 
  - $dE/dx \text{ K}/\pi \text{ sep} = 1.4\sigma$  ( $p > 2 \text{ GeV}$ )
- Silicon Vertex detector (1+5+2 layers)  
I.P. resolution  $35 \mu\text{m}@2 \text{ GeV}$

- CDF(Trigger):

- Drift chamber tracks: eXtremely Fast Tracker (at L1)
- Silicon Vertex Trigger (at L2). Allows **powerful triggers based on impact parameters and transverse B decay length, (unique to CDF)**

$L_{\text{int}} \sim 2 \text{ fb}^{-1}$  on tape  
( $\sim 1.6 \text{ fb}^{-1}$  for analysis)

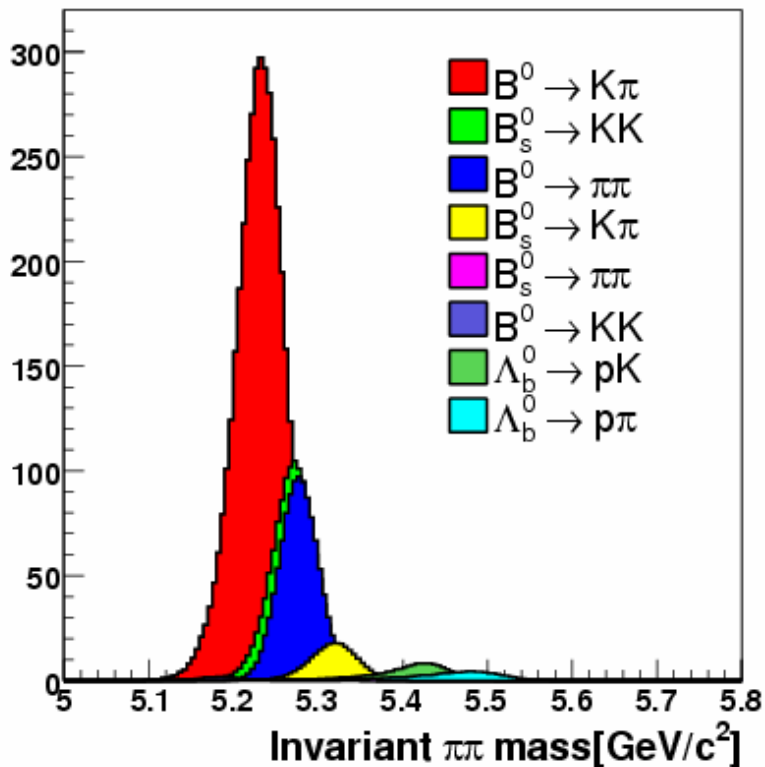


Results here use  $\sim 1 \text{ fb}^{-1}$

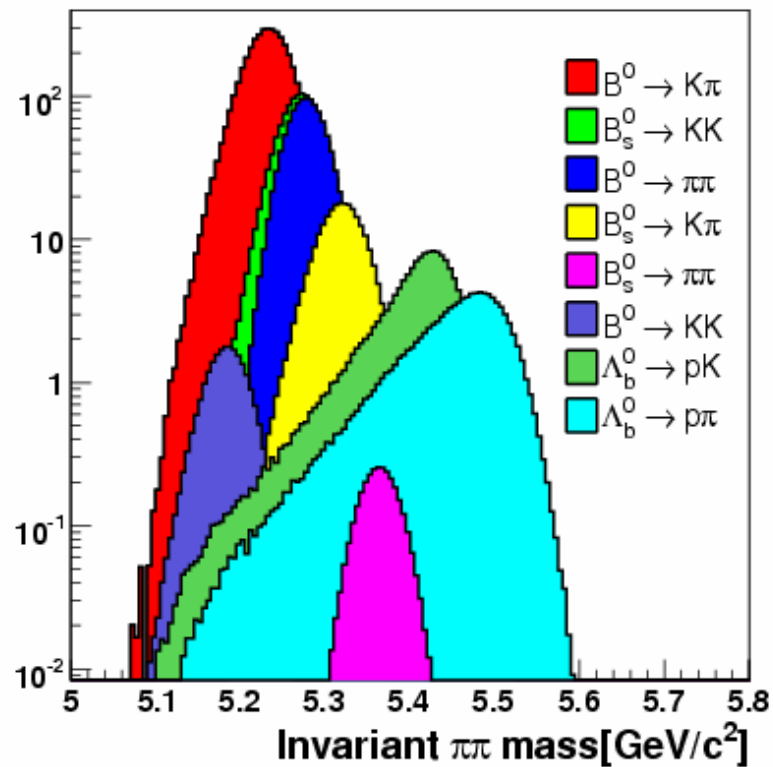


# Signal composition

CDF Run II Monte Carlo



CDF Run II Monte Carlo





# $A_{CP}(B^0 \rightarrow K^+ \pi^-)$ cuts: other fit parameters

## Combinatorial background

parameter	value
$f_{\pi^+}$ (combinatorial)	$0.545 \pm 0.017$
$f_{e^+}$ (combinatorial)	$0.036 \pm 0.005$
$f_p$ (combinatorial)	$0.080 \pm 0.025$
$f_{K^+}$ (combinatorial)	$0.337 \pm 0.031$
$f_{\pi^-}$ (combinatorial)	$0.533 \pm 0.018$
$f_{e^-}$ (combinatorial)	$0.030 \pm 0.005$
$f_{\bar{p}}$ (combinatorial)	$0.132 \pm 0.027$
$f_{K^-}$ (combinatorial)	$0.304 \pm 0.033$

## $B \rightarrow 3$ body background

fraction of physics bckg (ARGUS norm.)	$0.197 \pm 0.016$
ARGUS cut-off [ $\text{GeV}/c^2$ ]	$5.135 \pm 0.001$
ARGUS shape	$8.467 \pm 3.45$
$f_{\pi}$ (ARGUS)	$0.728 \pm 0.027$
$f_K$ (ARGUS)	$0.272 \pm 0.027$
background fraction	$0.481 \pm 0.008$
$c_1$ (background shape)	$-1.221 \pm 0.124$



# Significance Table

(Statistical + systematic)

raw yield  $\pm$  stat.  
from fit on data

systematic error

mode	yield	TOY stat. ( $f = 0$ )	syst.	Sign.(TOY stat. ( $f = 0$ ) + syst.)
$B^0 \rightarrow K^+ K^-$	$61 \pm 25$	21	35	$1.5\sigma$
$B_s^0 \rightarrow \pi^+ \pi^-$	$26 \pm 16$	11	14	$1.5\sigma$
$B_s^0 \rightarrow K^- \pi^+$	$230 \pm 34$	23	16	$8.2\sigma$
$\Lambda_b^0 \rightarrow p \pi^-$	$110 \pm 18$	9	16	$5.9\sigma$
$\Lambda_b^0 \rightarrow p K^-$	$156 \pm 20$	8	11	$11.5\sigma$

statistical uncertainty from pseudo  
experiments where the fractions of  
rare modes are fixed =0.

statistical error from the  
pseudo-experiment +  
systematic error. (Sum in  
quadrature).



$$A_{\text{CP}}(B_s^0 \rightarrow K^- \pi^+)$$

$$A_{\text{CP}} = \frac{N(\bar{B}_s^0 \rightarrow K^+ \pi^-) - N(B_s^0 \rightarrow K^- \pi^+)}{N(\bar{B}_s^0 \rightarrow K^+ \pi^-) + N(B_s^0 \rightarrow K^- \pi^+)} = 0.39 \pm 0.15 \text{ (stat.)} \pm 0.08 \text{ (syst.)}$$

SM predicts that [Lipkin, Phys. Lett. B621:126, .2005]:

$$|A(B_s \rightarrow \pi^+ K^-)|^2 - |A(\bar{B}_s \rightarrow \pi^- K^+)|^2 = |A(\bar{B}_d \rightarrow \pi^+ K^-)|^2 - |A(B_d \rightarrow \pi^- K^+)|^2$$

CDF measure:

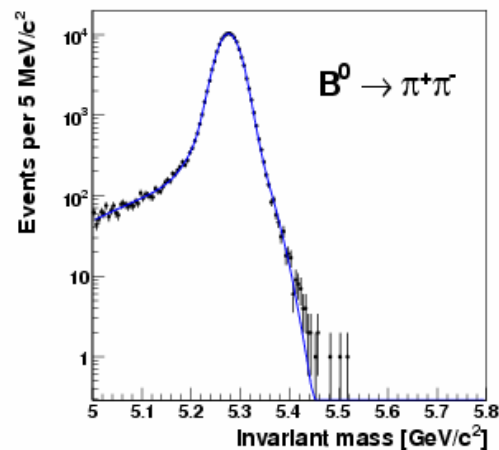
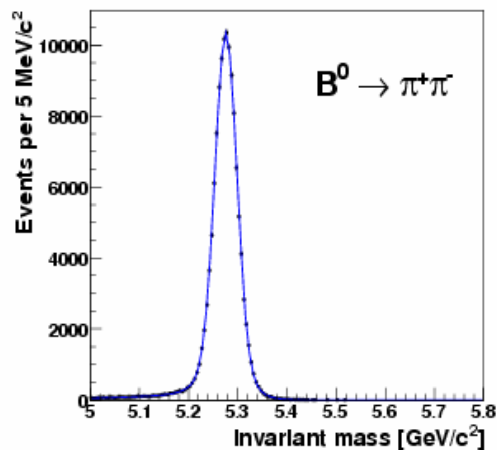
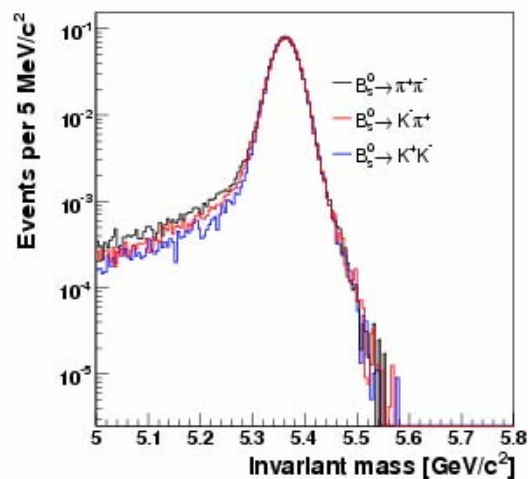
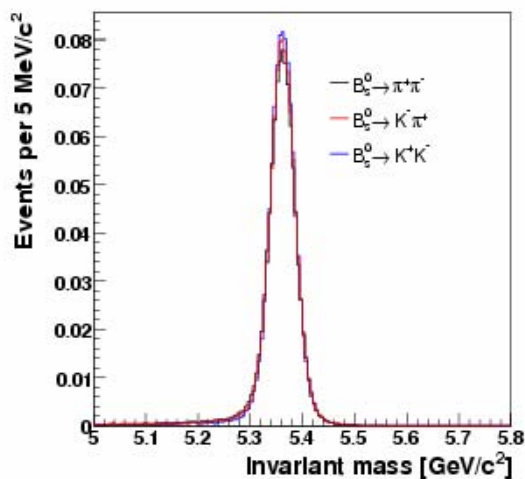
$$\frac{N(\bar{B}^0 \rightarrow K^- \pi^+) - N(B^0 \rightarrow K^+ \pi^-)}{N(\bar{B}_s^0 \rightarrow K^+ \pi^-) - N(B_s^0 \rightarrow K^- \pi^+)} = -3.21 \pm 1.60 \text{ (stat.)} \pm 0.39 \text{ (syst.)}$$

using HFAG:

$$\frac{|A(\bar{B}_d \rightarrow \pi^+ K^-)|^2 - |A(B_d \rightarrow \pi^- K^+)|^2}{|A(B_s \rightarrow \pi^+ K^-)|^2 - |A(\bar{B}_s \rightarrow \pi^- K^+)|^2} = 0.84 \pm 0.42 \text{ (stat.)} \pm 0.15 \text{ (syst.)} (=1 \text{ SM})$$



# Mass templates





# Efficiency of the isolation cut ( $180\text{pb}^{-1}$ )

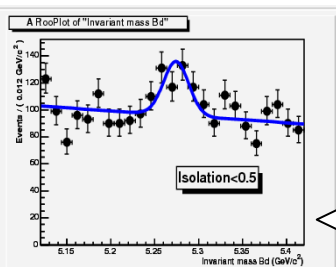
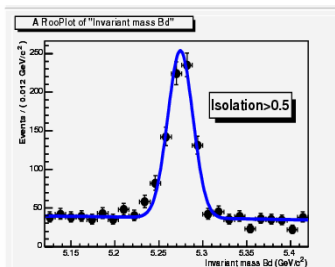
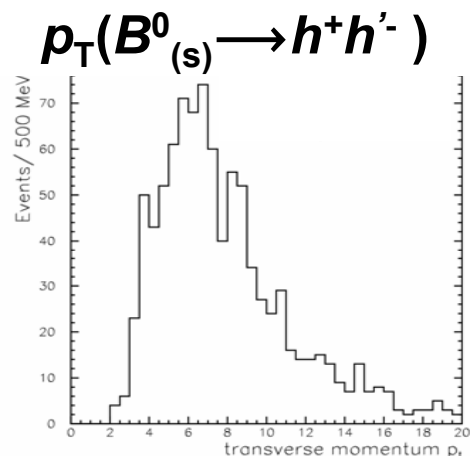
Isolation: fraction of  $p_T$  carried by the  $B$  meson with respect to total  $p_T$  of tracks produced in fragmentation.

Not obvious that Monte Carlo reproduces it.

Use data to extract  $p_T$ -dependent efficiency.

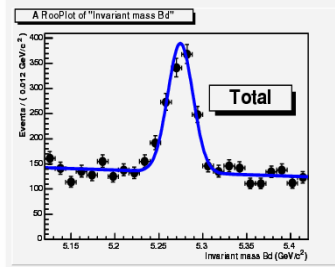
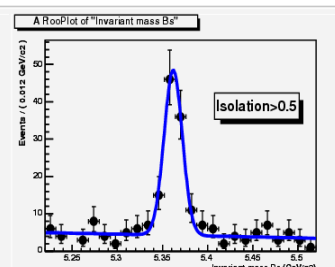
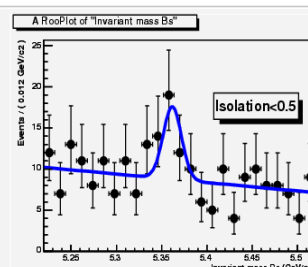
Need low- $p_T$  samples: low edge of  $p_T \sim 3$  GeV

Maximum Likelihood fit of yield in exclusive modes.

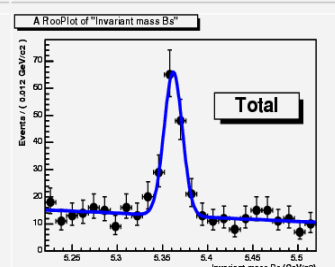


$$B^0_s \rightarrow J/\psi \Phi$$

$$B^0 \rightarrow J/\psi K^{*0}$$



GeV/c	$\epsilon_{Iso}(B_d)$	$\epsilon_{Iso}(B_s)$	$\epsilon_{Iso}(B_d)/\epsilon_{Iso}(B_s)$
$p_T(B) < 6$	$57.5 \pm 9.7$	$70.1 \pm 14.6$	$0.82 \pm 0.22$
$6 < p_T(B) < 10$	$84.6 \pm 2.4$	$84.8 \pm 5.7$	$1.00 \pm 0.08$
$p_T(B) > 10$	$93.8 \pm 1.2$	$90.4 \pm 2.8$	$1.04 \pm 0.03$

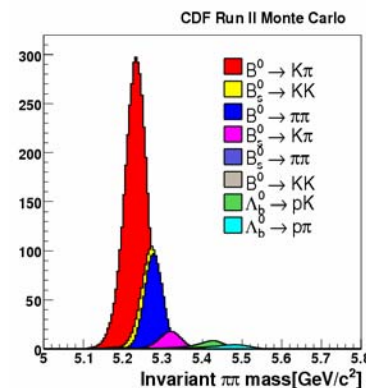




# $B^0 \rightarrow \pi^+ \pi^- / B^0 \rightarrow K^+ \pi^-$ ratio of decay rates

$$\frac{BR(B^0 \rightarrow \pi^+ \pi^-)}{BR(B^0 \rightarrow K^+ \pi^-)} = \frac{N(B^0 \rightarrow \pi^+ \pi^-)}{N(B^0 \rightarrow K^+ \pi^-)} \bigg|_{\text{raw}} \cdot \frac{\epsilon_{kin}(B^0 \rightarrow K^+ \pi^-)}{\epsilon_{kin}(B^0 \rightarrow \pi^+ \pi^-)} \cdot \frac{c_{XFT}(B^0 \rightarrow K^+ \pi^-)}{c_{XFT}(B^0 \rightarrow \pi^+ \pi^-)}$$

Different efficiency of the selection due to kinematical difference between the decays, and different decay-in-flight and interaction probability between  $K$  and  $\pi$ . Get from Monte Carlo the ratio of kinematics efficiencies.  $\sim 3\%$  correction



$\pi$  ionize more than  $K$ ; this introduces a bias in the trigger on tracks within the drift chamber (XFT). Use data from unbiased legs in  $D^+ \rightarrow K^- \pi^+ \pi^+$  sample.  $\sim 5\%$  correction

